# Flavor Changing Neutral Currents and Rare Top Decays

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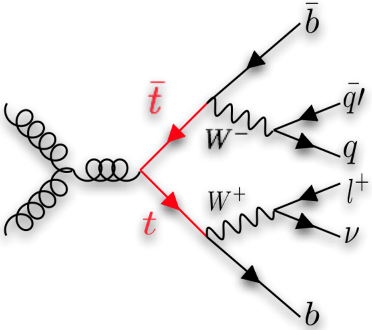
# Outline

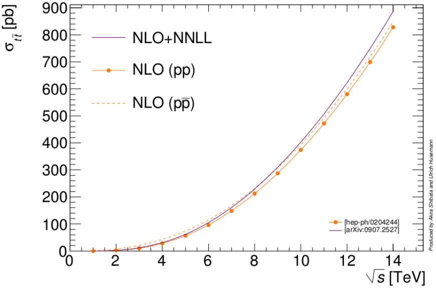




# Introduction

## New physics with the top quark

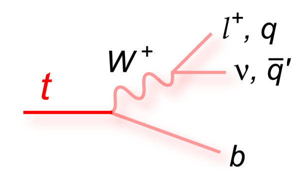
- large mass $\Rightarrow$ radiative corrections more important than for lighter fermions
- high productions cross-section at LHC @ 14 TeV,
  - $\sigma_{t\bar{t}} \sim \mathcal{O}(800pb)$
  - $\sigma_t \sim \mathcal{O}(300pb)$ (dominated by t-channel)



# Rare top decays

$$V_{CKM} = \begin{bmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{bmatrix}. \quad (1)$$

- top quarks decay overwhelmingly to $W + b$ in SM
- little mixing between $d$ and $s$ quarks as observed in CKM heirarchal structure




Measuring $V_{ts}$ and $V_{td}$ is difficult, so instead we measure $R$,

$$\mathcal{R} = \frac{Br(t \to Wb)}{Br(t \to Wq)} \quad (2)$$

# Results from the LHC

Measurements of $\mathcal{R}$ have been done by CMS* at both $\sqrt{s} = 7$ (8) TeV using $L_{int} = 2.2$ (16.8) $\text{fb}^{-1}$.

## Event selection

- Select on $t\bar{t}$ events
  - 2 prompt isolated leptons with $p_{T,\ell} > 20$ GeV and $|\eta| < 2.4$
  - MET $> 40$ GeV
  - $N_{jets} > 2$; jet $p_T > 30$ GeV and $|\eta| < 2.4$
  - $\Delta R(\ell, jet) > 0.3$
- kill dominant $Z + X$ background by requiring $|M_{ll} - M_Z| > 15$ GeV

Data is divided into three lepton flavor categories ($ee$, $e\mu$, and $\mu\mu$) and by the number of jets seen in the event.

* CMS PAS TOP-11-029, CMS PAS TOP-12-035

## Event yields

| Source | $ee$ | $e\mu$ | $\mu\mu$ |
|---|---|---|---|
| Single top | $284 \pm 11 \pm 16$ | $1134 \pm 22 \pm 64$ | $438 \pm 14 \pm 24$ |
| VV | $165 \pm 3 \pm 9$ | $650 \pm 6 \pm 39$ | $262 \pm 4 \pm 16$ |
| Multijets/$W \to \ell\nu$ | $18 \pm 3 \pm 18$ | $47 \pm 6 \pm 47$ | $4 \pm 2 \pm 4$ |
| $Z/\gamma^* \to \ell\ell$ | $1827 \pm 61 \pm 226$ | $998 \pm 32 \pm 110$ | $2757 \pm 69 \pm 188$ |
| other $t\bar{t}$ | $9 \pm 2 \pm 2$ | $58 \pm 6 \pm 6$ | $21 \pm 3 \pm 3$ |
| $t\bar{t}$ +V | $24 \pm 1 \pm 1$ | $79 \pm 1 \pm 4$ | $37 \pm 1 \pm 2$ |
| signal $t\bar{t}$ dilepton | $5080 \pm 13 \pm 407$ | $21040 \pm 30 \pm 1528$ | $8130 \pm 17 \pm 565$ |
| Total | $7407 \pm 64 \pm 467$ | $24006 \pm 50 \pm 1534$ | $11649 \pm 73 \pm 597$ |
| Data | 7254 | 24021 | 11423 |

## Event purity

As an input for the determination of $\mathcal{R}$ is the purity of the event,

$$f_{t\bar{t}} = \mu \frac{N_{t\bar{t},exp}}{obs} \tag{3}$$

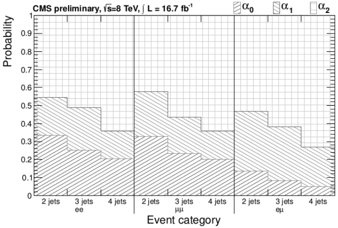
and $k_{st}$ which is the relative contribution from single top events.

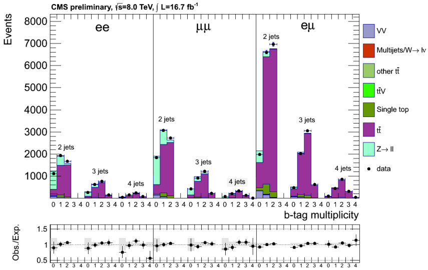
| Contribution | Channel | $ee$ | $e\mu$ | $\mu\mu$ |
|---|---|---|---|---|
| $f_{t\bar{t}}$ | 2 jets | $0.647 \pm 0.056$ | $0.861 \pm 0.052$ | $0.666 \pm 0.047$ |
| | 3 jets | $0.739 \pm 0.069$ | $0.913 \pm 0.066$ | $0.755 \pm 0.065$ |
| | 4 jets | $0.775 \pm 0.091$ | $0.938 \pm 0.092$ | $0.771 \pm 0.087$ |
| $k_{st}$ | 2 jets | $0.065 \pm 0.007$ | $0.062 \pm 0.005$ | $0.062 \pm 0.006$ |
| | 3 jets | $0.047 \pm 0.004$ | $0.043 \pm 0.009$ | $0.039 \pm 0.006$ |
| | 4 jets | $0.040 \pm 0.009$ | $0.031 \pm 0.006$ | $0.047 \pm 0.010$ |

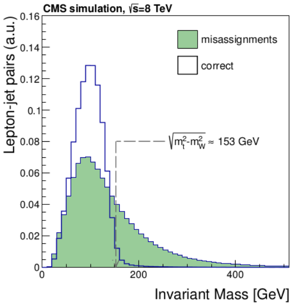
# Jet misassignment and heavy flavor content

## Important parameters

- b-tagging efficiency, $\epsilon_b$
- jet misidentification rate, $\alpha_k$
- heavy flavor content
- Data-MC corrections, $f_{corr}$



# Measurement of $\mathcal{R}$

The value of $\mathcal{R}$ is extracted from the data using a binned likelihood fit,

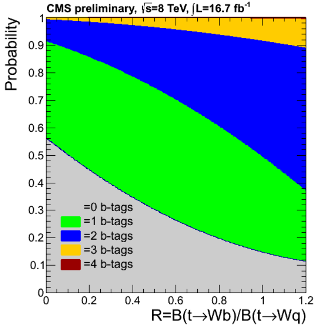
$$\mathcal{L}(\mathcal{R}, f_{t\bar{t}}, k_{st}, f_{correct}, \varepsilon_b, \varepsilon_q, \varepsilon_{q*}, \theta_i) = \prod_{\ell\ell} \prod_{\text{jets}\geq 2} \prod_{k=0}^{\text{jets}} \mathcal{P}\left[N_{ev}^{\ell\ell,jets}(k), \hat{N}_{ev}^{\ell\ell,jets}(k)\right] \times \prod_i \mathcal{G}_{aus}(\theta_i^0, \theta_i, 1) \quad (4)$$

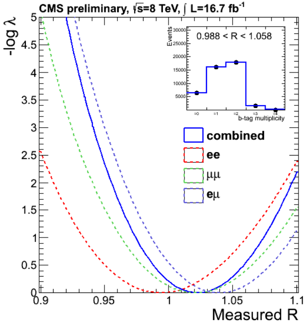
The parameters of the fit are taken from values obtained above, and nuisance parameters are assumed to be unbiased and normally distributed. the value of

$\mathcal{R}$ the can be determined by forming a profile likelihood ratio,

$$\lambda(\mathcal{R}) = \frac{\mathcal{L}(\mathcal{R}, \hat{\theta})}{\mathcal{L}(\hat{\mathcal{R}}, \hat{\theta})} \quad (5)$$

# Results




The value of $\mathcal{R}$ is interpreted under two assumptions...

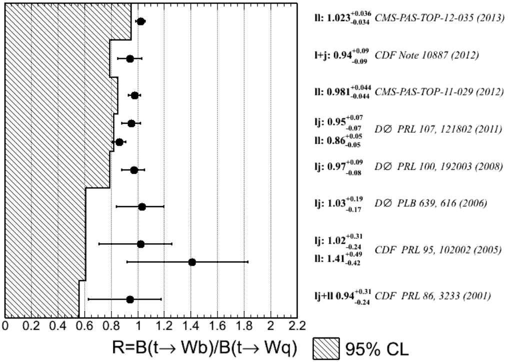
**Assume CKM unitarity ($\mathcal{R} \leq 1$)**

$$\mathcal{R} > 0.945$$
$$|V_{tb}| > 0.972$$

**No constraint on $\mathcal{R}$**

$$\mathcal{R} = 1.023^{+0.036}_{-0.034}$$
$$|V_{tb}| = 1.011^{+0.018}_{-0.017}$$

# Summary




## 14 TeV Projection

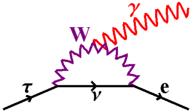
Systematic uncertainty "saturates" with addition of more 8 TeV data. No obvious strategy for reducing uncertainties to $< 1\%$ level required by theorists. No preliminary numbers at the moment.

# Flavor Changing Neutral Currents

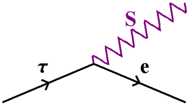
## GIM mechanism

In the SM, tree-level FCNC decays are suppressed due to the GIM mechanism and limited mixing between generations.
$\Rightarrow$ Observation of FCNC decays may give us hints into new physics.

**Standard Model FCNC**




**Beyond–the–SM FCNC**




| Decay | SM | Quark singlet | MSSM | $\cancel{R}$ SUSY | 2HDM |
|---|---|---|---|---|---|
| $t \to qZ$ | $10^{-14}$ | $10^{-4}$ | $10^{-6}$ | $10^{-5}$ | $10^{-7}$ |
| $t \to q\gamma$ | $10^{-14}$ | $10^{-8}$ | $10^{-6}$ | $10^{-6}$ | $10^{-6}$ |
| $t \to qg$ | $10^{-12}$ | $10^{-7}$ | $10^{-4}$ | $10^{-4}$ | $10^{-4}$ |
| $t \to qH$ | $10^{-15}$ | $10^{-5}$ | $10^{-5}$ | $10^{-6}$ | $10^{-3}$ |

# Search channels

## In this talk

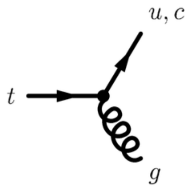
$t \to qZ$ Investigate $t\bar{t}$ events with one $t$ decaying as usual ($t \to Wb$) and the other through $t \to qZ$

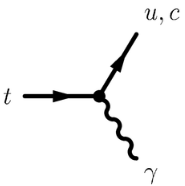
$t \to qH$ Similar to $t \to qZ$, but with many different final state options. Multilepton ($\geq 3$) final states, same-sign dilepton, or single lepton plus $\geq 3$ b-jets are all possible search channels.

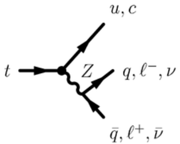
## Not in this talk

$t \to qg$ Investigate single top + jet events. $\text{Br}(t \to c(u)g) < 2.7 \times 10^{-4} (5.7 \times 10^{-5})$ (arXiv:1203.0529)

$t \to q\gamma$ Investigate single top + $\gamma$ events.



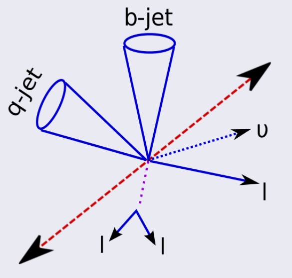



# $t \to qZ$

ATLAS, CMS, and D0 have all carried out investigations of $t \to qZ$ with similar analysis strategies. Consider the CMS analysis...

## Event selection




**Preselection**

- 3 prompt, well-isolated leptons
- $\not{E} > 30$ GeV
- at least 2 jets ($p_T > 30$ GeV)
- 2 leptons form Z candidate

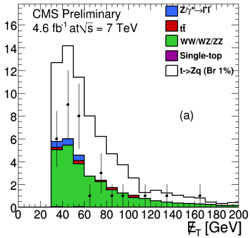
**Additional cuts**

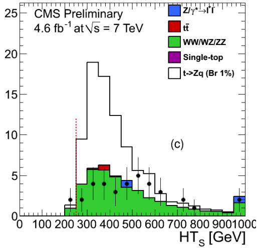
- require b-tagged jet or cut on $HT_s$*
- Z+jet reconstructs top
- W+b-jet reconstructs top

* $HT_s = \sum p_T^{\ell} + \sum p_T^{jets} + \not{E}$

# Preselection

| Channel | $\mu\mu e$ | $\mu\mu\mu$ | $eee$ | $ee\mu$ |
|---|---|---|---|---|
| Drell–Yan | $2.0 \pm 1.4 \pm 0.3$ | $0.9 \pm 1.0 \pm 0.1$ | $2.8 \pm 1.7 \pm 0.4$ | $0.9 \pm 1.0 \pm 0.1$ |
| $WZ$ | $46.1 \pm 6.8 \pm 6.1$ | $60.3 \pm 7.8 \pm 8.0$ | $40.9 \pm 6.4 \pm 5.4$ | $48.6 \pm 7.0 \pm 6.4$ |
| $ZZ$ | $17.7 \pm 4.2 \pm 2.3$ | $21.7 \pm 4.7 \pm 2.9$ | $15.1 \pm 3.9 \pm 2.0$ | $18.2 \pm 4.3 \pm 2.4$ |
| $WW$ | $\leq 0.001$ | $\leq 0.001$ | $0.2 \pm 0.3 \pm 0.0$ | $\leq 0.001$ |
| $t\bar{t}$ | $\leq 0.001$ | $0.5 \pm 0.7 \pm 0.1$ | $0.9 \pm 0.9 \pm 0.1$ | $0.9 \pm 0.9 \pm 0.1$ |
| Single-top | $\leq 0.001$ | $0.1 \pm 0.4 \pm 0.0$ | $0.0 \pm 0.2 \pm 0.0$ | $\leq 0.05$ |
| Total | $66 \pm 8 \pm 7$ | $84 \pm 9 \pm 9$ | $60 \pm 8 \pm 6$ | $69 \pm 8 \pm 7$ |
| Data | 73 | 87 | 85 | 61 |

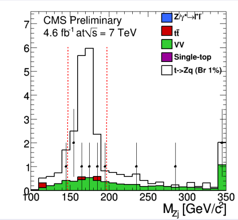


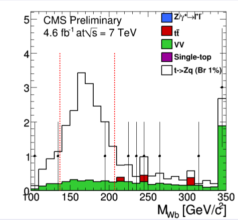




Dominant background after preselection is diboson

## b-tag selection

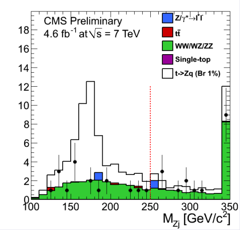
- require exactly one b-tagged jet
- tight requirements on both $M_{Zj}$ and $M_{Wb}$

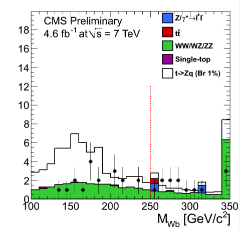



## $HT_s$ selection

- require $HT_s > 200$ GeV
- loose requirements on both $M_{Zj}$ and $M_{Wb}$



# Results and projections

| Signal Selection | $HT_S$-cut Based | $b$-tag Based |
|---|---|---|
| Total background prediction (data driven) | $16.2 \pm 3.9 \pm 2.6$ | $0.6 \pm 0.1 \pm 0.1$ |
| Data | 11 | 0 |
| Expected limit at the 95% CL | $Br(t \to Zq) < 0.42\%$ | $Br(t \to Zq) < 0.34\%$ |
| Observed limit at the 95% CL | $Br(t \to Zq) < 0.39\%$ | $Br(t \to Zq) < 0.34\%$ |

## CMS limits

Limits are set using modified frequentist approach and are based on 4.6 $\text{fb}^{-1}$ of data taken at $\sqrt{s} = 7$ TeV.,

- No excess observed over SM prediction for both event selection strategies
- Expected bounds on limits are $0.30\% - 0.64\%$ ($0.34\% - 0.48\%$)for $HT_s$ (b-tag) selection.

Assuming similar systematics and $S/B$, we can project to an upper limit of 0.01% with 300 $\text{fb}^{-1}$ at 14 TeV

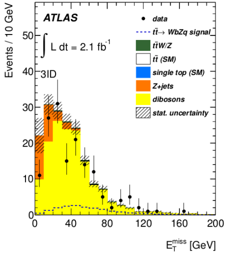
See **CMS TOP-11-028**

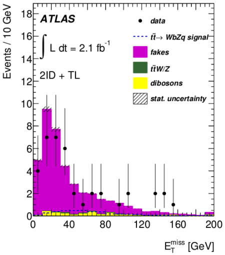
# ATLAS search

## differences from CMS

- consider 2 lepton categories:
  - 3 tight-ID leptons
  - 2 tight-ID leptons + 1 “track” lepton
- enforce consistency of $t\bar{t} \to ZqWb$ decay by minimizing
- 2.1fb$^{-1}$

$$\chi^2 = \frac{\left(m^{reco}_{j_a\ell_a\ell_b} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{j_b\ell_c\nu} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{\ell_c\nu} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m^{reco}_{\ell_a\ell_b} - m_Z\right)^2}{\sigma_Z^2} \quad (6)$$




See **arxiv:1206.0257**

# ATLAS results

| | 3ID | 2ID+TL |
|---|---|---|
| $ZZ$ and $WZ$ | $9.5 \pm 4.4$ | $1.0 \pm^{0.5}_{0.6}$ |
| $t\bar{t}W$ and $t\bar{t}Z$ | $0.51 \pm 0.14$ | $0.25 \pm 0.05$ |
| $t\bar{t}$, $WW$ | $0.07 \pm 0.02$ | |
| $Z$+jets | $1.7 \pm 0.7$ | $7.6 \pm 2.2$ |
| Single top | $0.01 \pm 0.01$ | |
| 2+3 fake leptons | $0.0 \pm^{0.2}_{0.0}$ | |
| Expected background | $11.8 \pm 4.4$ | $8.9 \pm 2.3$ |
| Data | 8 | 8 |
| Signal efficiency | $(0.205 \pm 0.024)\%$ | $(0.045 \pm 0.007)\%$ |

## Limits

- determined using modified frequentist approach at 95% CL
- consistent with CMS result

| channel | observed | $(-1\sigma)$ | expected | $(+1\sigma)$ |
|---|---|---|---|---|
| 3ID | 0.81% | 0.63% | 0.95% | 1.4% |
| 2ID+TL | 3.2% | 2.15% | 3.31% | 4.9% |
| Combination | 0.73% | 0.61% | 0.93% | 1.4% |

# Flavor Changing Neutral Higgs

With the newly discovered Higgs(-like) boson with a mass of 125 GeV, detailed measurements of its decay properties are now underway.

## Flavor-violation in an effective coupling

The Higgs couples to up-type quarks via a coupling of the form,

$$m_{ij} u_i \bar{u}_j + \lambda^h_{ij} h u_i \bar{u}_j + h.c. \tag{7}$$

The branching ratio with an effective Higgs interaction with flavor violating can be derived,

$$Br(t \to ch) \simeq \frac{|\xi_{tc}|^2 + |\xi_{ct}|^2}{8\sqrt{2} G_F^3 m_t^2 M^4 |V_{tb}^2} \frac{(1 - m_h^2/m_t^2)^2}{(1 - m_W^2/m_t^2)^2 (1 + 2m_W^2/m_t^2)} \tag{8}$$

$$\simeq 0.29(|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2) \tag{9}$$

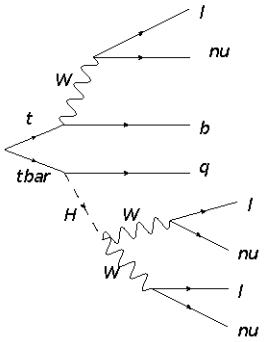
Estimates for Br($t \to Hq$) $\approx 10^{-2} - 10^{-3}$ in a 2HDM.

T. P. Cheng and M. Sher, "Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets," Phys. Rev. D **35**, 3484 (1987).

# Search strategies

## Searches

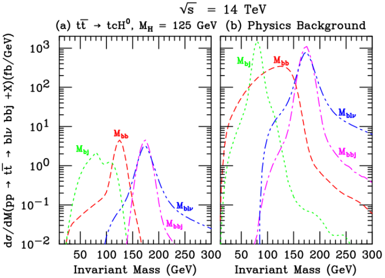
- Investigation of the presence of $t \to Hq$ can be done with a similar strategy to $t \to Zq$ analysis
  - assume $t\bar{t}$ production
  - allow one $t$ to decay normally ($t \to Wb$)
  - require the other decay as $t \to Hq$
- Many more possible decay channels available to Higgs; $WW$, $ZZ$, $\tau\tau$, or $b\bar{b}$ are all potentially viable search channels

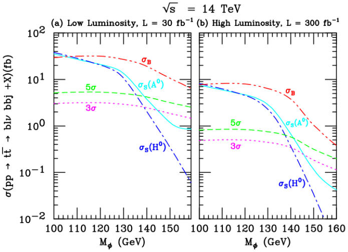


# Feasibility study with $H \to b\bar{b}$ final states

## Acceptance cuts

- at least 3 b-jets ($p_T > 15$ GeV)
- exactly one well isolated, prompt lepton ($p_T > 20$ GeV)
- MET $> 20$ GeV
- enforce decays through cuts on $M_{b_1 b_2 \ell}$, $M_{b_3 \ell \nu}$, etc.




## Projected limits

- sensitivity to $3\sigma$ deviation at 8 TeV with $\sim 20\text{fb}^{-1}$
- potential to observe $+5\sigma$ deviation at 14 TeV with $\gtrsim 30\text{fb}^{-1}$
- See Kao, et. al.;(arxiv:1112.1707)

# First results from CMS multi-lepton search

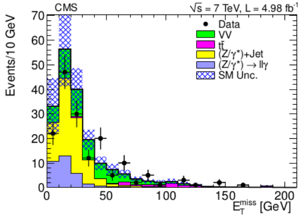
Based on a generalized multi-lepton search (arXiv:1112.2298), an initial limit can be placed on $\mathrm{Br}(t \to hc)$.

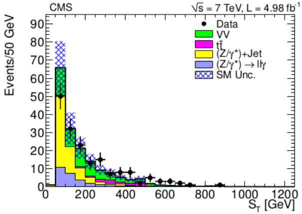
## strategy

$4.89\ \mathrm{fb}^{-1}$ of data collected at $\sqrt{s} = 7$ TeV is divided into several categories/bins based on,

- number of leptons ($N_\ell = 3, 4$)
- MET
- $H_T$ ($= \sum p_T^{jets}$) or $HT_S$

The resulting yields can then be compared against a given signal model.



| | | | Observed | Expected | Signal |
|---|---|---|---|---|---|
| 4 Leptons | | | | | |
| MET HIGH | HT HIGH | No Z | 0 | $0.018 \pm 0.005$ | 0.02 |
| MET HIGH | HT HIGH | Z | 0 | $0.22 \pm 0.05$ | 0.0 |
| MET HIGH | HT LOW | No Z | 1 | $0.2 \pm 0.07$ | 0.11 |
| MET HIGH | HT LOW | Z | 1 | $0.79 \pm 0.21$ | 0.04 |
| MET LOW | HT HIGH | No Z | 0 | $0.006 \pm 0001$ | 0.0 |
| MET LOW | HT HIGH | Z | 1 | $0.83 \pm 0.33$ | 0.04 |
| MET LOW | HT LOW | No Z | 1 | $2.6 \pm 1.1$ | 0.08 |
| MET LOW | HT LOW | Z | 33 | $37 \pm 15$ | 0.15 |
| 3 Leptons | | | | | |
| MET HIGH | HT HIGH | DY0 | 2 | $1.5 \pm 0.5$ | 0.48 |
| MET HIGH | HT LOW | DY0 | 7 | $6.6 \pm 2.3$ | 2.1 |
| MET LOW | HT HIGH | DY0 | 1 | $1.2 \pm 0.7$ | 0.26 |
| MET LOW | HT LOW | DY0 | 14 | $11.7 \pm 3.6$ | 1.68 |
| MET HIGH | HT HIGH | DY1 No Z | 8 | $5 \pm 1.3$ | 1.54 |
| MET HIGH | HT HIGH | DY1 Z | 20 | $18.9 \pm 6.4$ | 0.41 |
| MET HIGH | HT LOW | DY1 No Z | 30 | $27 \pm 7.6$ | 5.8 |
| MET HIGH | HT LOW | DY1 Z | 141 | $134 \pm 50$ | 2.0 |
| MET LOW | HT HIGH | DY1 No Z | 11 | $4.5 \pm 1.5$ | 0.80 |
| MET LOW | HT HIGH | DY1 Z | 15 | $19.2 \pm 4.8$ | 0.72 |
| MET LOW | HT LOW | DY1 No Z | 123 | $144 \pm 36$ | 3.1 |
| MET LOW | HT LOW | DY1 Z | 657 | $764 \pm 183$ | 2.4 |

Combining all channels, an observed limit of $\mathrm{Br}(t \to ch) < 2.7\%$ is calculated at 95% CL with an expected limit of $\mathrm{Br}(t \to ch) < 1.7\%$.

# Conclusions

## Rare decays

- CMS has made most precise measurement of $|V_{tb}|$ to date.
- improvements on precision may be limited by systematics

## FCNC

- ATLAS and CMS have put limits on several FCNC channels
- Projections for next LHC run suggest $\times 10$ increse in sensitivity
- First limit put on $t \to qH$ decay; expect analysis of 8 TeV data later this year